Improved Ecosystem Predictions of the California Current System via Accurate Light Calculations

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LONG-TERM GOAL

The goal of this effort is to incorporate extremely fast but accurate light calculations into coupled physical-biological-optical ocean ecosystem models as used for operational three-dimensional ecosystem predictions. Improvements in light calculations will lead to improvements in predictions of chlorophyll concentrations and other water-quality parameters (such as visibility) relevant to naval needs.

OBJECTIVES

Currently available ecosystem models often use fairly sophisticated treatments of the physics (e.g., advection and upper-ocean thermodynamics and mixing) and biology (e.g., primary production, nutrient utilization, and grazing) but use grossly oversimplified treatments of the optics. The optics component of coupled ecosystem models is sometimes just a single equation parameterizing the scalar irradiance in terms of the chlorophyll concentration and a few parameters such as the solar zenith angle. Such simple light models often fail even in Case 1 waters, and they can be wrong by orders of magnitude in Case 2 or optically shallow waters.

The objective of this effort is therefore to further improve the previously developed EcoLight radiative transfer model and incorporate it into a three-dimensional, time-dependent, coupled physical-biological-optical ecosystem model. That coupled model will be used to evaluate various strategies for updating the in-water spectral irradiance so as to obtain accurate ecosystem predictions while maintaining acceptably fast computation times in fully 3D simulations. In particular, we will address questions about how often in time and space the spectral irradiance needs to be updated when modeling complex and dynamic ecosystems. The test bed for this work is a 3D ROMS-CoSINE physical-biological model with idealized boundary conditions. Later work will imbed EcoLight into the NCOM-CoSINE model for application to the California Current System and the Monterey Bay area.

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APPROACH

ONR has previously funded (see the report on contract N00014-08-C-0024) the development of EcoLight, a very fast radiative transfer model designed for use in coupled physical-biological-optical ecosystem models. During its development and initial evaluations EcoLight was imbedded in an idealized ecosystem model based on a special version of the ROMS-EcoSim physical-biological model with a 6x6 horizontal grid and periodic lateral boundary conditions. That code was developed by P. Bissett at the Florida Environmental Research Institute and his collaborators in the ROMS group at Rutgers University. ROMS (Regional Ocean Modeling System) is described in Shchepetkin and McWilliams (2005; www.myroms.org). EcoSim is described in (Bissett, *et al.*, 1999a, 1999b, 2004). The periodic-boundary version of ROMS-EcoSim was chosen for development and initial evaluation of EcoLight because of its geometric simplicity and small run times. Ten-year simulations of an idealized open-ocean, Case 1 water, ecosystem showed that EcoLight can replace the simple analytic light model used in the original EcoSim code with less than a 30% increase in total run times. That previous work is described in Mobley et al. (2009).

Although both the EcoSim analytic and EcoLight numerical spectral irradiances gave comparable chlorophyll predictions for ten-year simulations of open-ocean Case 1 waters, such agreement cannot be expected in simulations of Case 2 waters, for which analytic light models can be in error by a factor of ten or more. Likewise, chlorophyll-based analytic light models will underestimate the scalar irradiance in simulations of optically shallow waters with bright reflective bottoms. In such waters, bottom reflectance significantly increases the in-water scalar irradiance and proportionately affects biological productivity and water-column heating rates. The EcoLight solution of the radiative transfer equation (RTE) to a given optical depth is not dependent on whether the inherent optical properties (IOPs, namely the absorption and scattering properties of the water body) describe Case 1 or 2 water. Its fast run times seen in the simulations of Case 1 water will therefore be retained in applications to other water bodies. Unlike simple analytic light models, EcoLight can account for the effects of shallow bottoms and is valid for Case 2 waters. EcoLight also computes related quantities such as the nadir-viewing remote-sensing reflectance corresponding to the bio-optical state of the ecosystem. This allows for validation of ecosystem model predictions using satellite ocean color radiometry, without an intervening step to convert a satellite-measured radiance to a chlorophyll concentration via an imperfect chlorophyll algorithm.

Given the success of EcoLight in its initial evaluation, the next step is to incorporate EcoLight into a fully 3D ecosystem model, which is being done in the work described here. The test bed for this work is a 3D ROMS-CoSINE physical-biological model with idealized 3D boundary conditions. The CoSINE (Carbon, Silicate, and Nitrogen Ecosystem) model is described in Chai et al., (2002, 2003, and 2007) and Fujii et al. (2007). Later work will incorporate EcoLight into the NCOM (Navy Coastal Ocean Model)-CoSINE model for application to the California Current System and the Monterey Bay area.

The EcoLight optical model. EcoLight solves the azimuthally averaged RTE to obtain irradiances with the same accuracy as the widely used industry-standard HydroLight numerical model (Mobley, 1994; www.hydrolight.info). The inputs for EcoLight are the same as for HydroLight, namely the IOPs of the water body, the incident sky radiance, and the bottom reflectance (in finite-depth waters). EcoLight takes the following philosophy. It is necessary to solve the RTE in order to incorporate the

effects of the surface boundary conditions and to account for all IOP effects. However, once an accurate value of the scalar irradiance $E_o(z,\lambda)$ has been computed to some depth z_o deep enough to be free of surface boundary effects, it is not necessary to continue solving the RTE to greater depths, which is computationally expensive. As shown in Mobley et al. (2009), in many cases of practical interest, it is possible to extrapolate the accurately computed upper-water-column irradiances to greater depths and still obtain irradiances that are acceptably accurate for ecosystem predictions. Likewise, it is not necessary to solve the RTE at every wavelength in order to obtain acceptably accurate irradiances at the needed wavelength resolution. Omitting every other wavelength, for example, cuts the run time by one half. It is certainly not necessary to update the in-water light field at every time step of the physical model, which is often only a few minutes as required for computational stability. EcoLight is packaged as a subroutine that allows it to be called from within an ecosystem model whenever updated values of $E_o(z,\lambda)$ are needed. That subroutine is used within a biological model to replace its analytic irradiance computations.

WORK COMPLETED

This work is just beginning. The EcoLight version 1.0 code used in Mobley et al. (2009) was written with the goal of getting it working correctly within the ROMS-EcoSim package, without much time being spent on streamlining the code. EcoLight 1.0 was called directly by the EcoSim code and therefore the input and output for the v. 1.0 code was particular to the EcoSim code in how information was passed between EcoSim and EcoLight.

Our first step in the present work is to rewrite the v. 1.0 code to (1) bring it up to the Fortran 95 standards of the ROMS-CoSINE code, (2) remove various un-needed calculations left over from HydroLight and, most importantly, (3) make the code independent of the particular physical-biological model calling it. The goal of this rewrite is to have a version 2.0 re-entrant "black-box" subroutine that can be called by any ecosystem model. This improved code is name EcoLight-S (Ecosystem Light Subroutine). To incorporate EcoLight-S into a particular physical-biological model, the user will write an interface subroutine to handle communication between the calling routine and EcoLight-S. When calling EcoLight-S, the interface will convert the physical-biological model outputs (component concentrations as a function of depth at a given time and grid location; other information such as time, location, sky conditions, bottom depth and reflectance in shallow waters; and wavelengths and depths where irradiances are needed by the calling model) into IOP and boundary-condition information on the format needed by EcoLight-S. After solving the RTE for the given IOPs and boundary conditions, EcoLight-S will return the spectral scalar irradiance and ancillary quantities (e.g., remote-sensing reflectance, down- and up-welling plane irradiances, and zenith and nadir radiances) at the requested depths and wavelengths. The interface module will reformat the EcoLight-S output as needed by the calling physical-biological model.

Each user of EcoLight-S thus will write an interface routine for the particular physical-biological model. The EcoLight-S inputs and outputs are fixed and documented. Thus an EcoLight-S user will not have to consider the internal workings of EcoLight-S, and the EcoLight-S code can be maintained and further developed without consideration of what physical-biological models will call it. EcoLight-S is thus an RTE solver only; it does not include IOP and other submodels, as does HydroLight. This scheme is illustrated in Fig. 1.
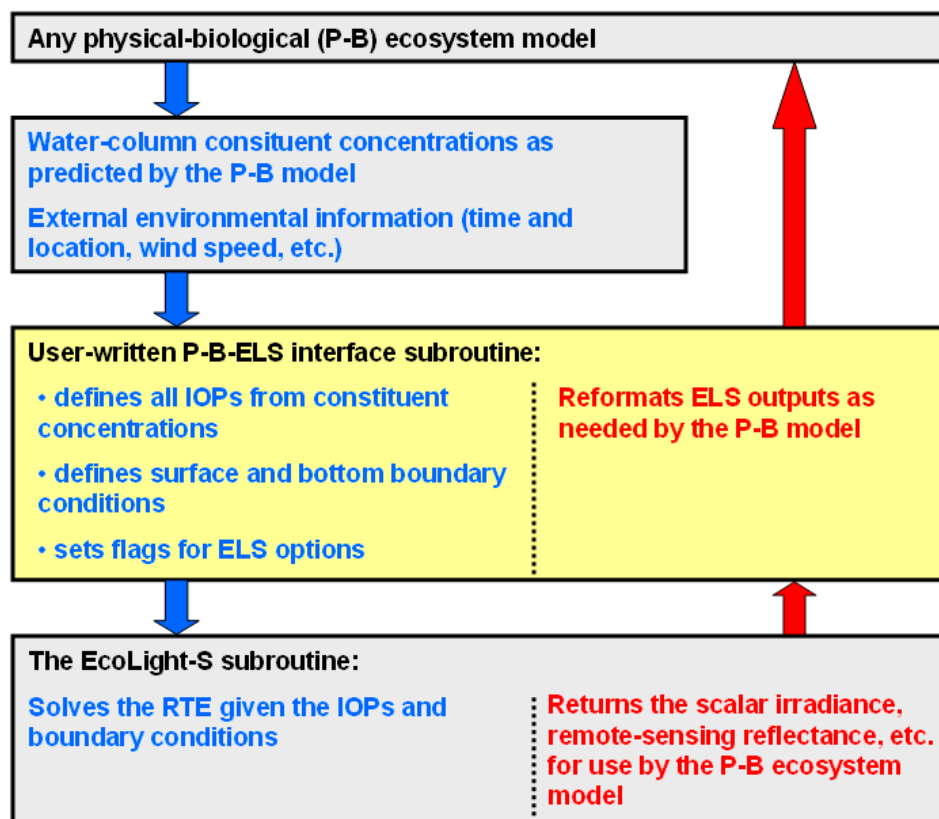
Fig. 1. Usage of EcoLight-S (ELS) within any coupled physical-biological ecosystem model. The interface subroutine makes EcoLight-S independent of the calling model. [The figure shows a flowchart of calculations in a coupled physical-biological-EcoLight-S ecosystem model.]

RESULTS

The rewrite of EcoLight 1.0 is nearing completion. The resulting EcoLight-S code and its use will be documented in a User's Guide once the code is in its final form.

We plan to begin incorporation of EcoLight-S into the 3D ROMS-CoSINE code by November, 2009. We will report on our work to date at an ecosystem modeling workshop to be held at Ispra, Italy December 14-18, 2009.

IMPACT/APPLICATION

Predictive ecosystem models are playing an increasingly important role in our understanding of the oceans. Applications of such models range from predictions of water clarity for military purposes to management of coastal waters for fisheries. The incorporation of the EcoLight-S model into coupled ecosystem models will give improved accuracy in the predictions of primary production and related quantities made by such models. As the coupled models become more trustworthy in their predictions, they will become even more valuable as tools for ocean science and aquatic ecosystem management. We therefore expect that EcoLight-S will find wide use beyond its initial applications here.

RELATED PROJECTS

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